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Cost-benefit analysis for multiple agents considering an electric vehicle charging/discharging strategy and grid integration

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Abstract—An increasing number of electric vehicles (EVs) will be charged/discharged in EV charging stations (EVCSS) in distribution systems. Grid-2-vehicle (G2V) and vehicle-2-grid (V2G) operation of EVs are economically and technically rewarding only when an optimal G2V/V2G strategy is properly developed. In this study, a scheduling scheme is developed which mainly focus on guaranteeing the rewards of all agents (e.g EVs, EVCSS, and electricity suppliers (ESs)) participating in V2G and G2V operation. Based on the proposed strategy, EVs independently plan their charging/discharging depending on the shortest driving route and cost/benefit offered by EVCSS. Furthermore, each EVCS finds the best ES to purchase electricity from the wholesale market. The benefits of all agents in EV's V2G and G2V operation are taken into account by formulating three optimization problems. Each problem belongs to each agent. To implement the proposed strategy, a cloud scheduling system is operated to collect required information from all agents, solve the optimization problems, and ultimately send the results to relevant agents. Optimal hourly electricity prices are determined for the three agents. For simulation purposes, nine EVCSSs and three ESs are facilitated for charging/discharging of EVs to visualize and validate the modeling results. The results show that by implementing the proposed strategy, the cost of EVs decreases by 18%, and the revenues of EVCSSs and ESs are raised by 21% and 23%, respectively, compared to the case in which EVs do not use the proposed strategy in EV's V2G and G2V operation.

Index Terms—Cloud scheduling system, electricity pricing, electric vehicles, multiple agents, optimization algorithm

Superscript

| | |
|-----------|--|
| CS | A charging station |
| $CS-, AG$ | Charging station sold to the aggregator |
| $CS-, EV$ | Charging station sold to the electric vehicle |
| $CS+, EV$ | Charging station purchased from electric vehicle |
| $CS+, ES$ | Charging station purchased from the electricity supplier |
| DEG | Degradation |
| EV | Electric vehicle |
| $EV+, CS$ | Electric vehicle purchased from the charging station |
| $EV-, CS$ | Electric vehicle sold to the charging station |
| ES | A electricity supplier |
| f | Follower |
| L | Leader |
| OP | Operation |
| $ES-, CS$ | Electricity supplier sold to the charging station |
| $ES+, WM$ | Electricity supplier purchased from wholesale market |

Subscript

| | |
|-----|---------------------------|
| n | Dimension |
| h | Hours of a day |
| i | Index of charging station |

Greek symbols

| | |
|--------|----------------|
| ρ | Price (\$/kWh) |
|--------|----------------|

NOMENCLATURE

| | |
|---------------|---|
| C | Cost (\$) |
| c_1 | Coefficient for balancing exploration |
| c_2, c_3 | Random number generated uniformly between 0 and 1 |
| F | Position of food source |
| \bar{it}/it | Maximum Number/Number of iterations |
| lb | Lower bound of variables |
| R | Revenue (\$) |
| ub | Upper bound of variables |
| x | Position of salp |

I. INTRODUCTION

Power systems are starting to experience higher and higher penetration of electric vehicles (EVs) due to the potential for reducing fossil fuel consumption. The EV batteries can store energy and use it in grid to vehicle (G2V) mode. Also, they are enable energy in EVs to be sent back into the grid to help supply energy at peak demand in vehicle to grid (V2G) mode. EVs can make profits based on the revenue obtained from energy trading in V2G operation [1]. Thus, the EV revolution will do more than reduce carbon emissions. Although, EVs provide unquestionable benefits to lower carbon

dioxide emission from transportation sector, they introduce some challenges. The most significant one is the uncoordinated G2V and V2G operation of EVs which implies higher risk of grid operation. Furthermore, the problem becomes more complicated when benefits of other agents participating in EV's V2G and G2V operation are taken into account. These agents are EV charging stations (EVCs) and electricity suppliers (ESs). EVCs provide electricity for EVs which must be charged and they are enable to purchase electricity from EVs in V2G mode. There are multiple EVCs which offer electricity with different prices to EVs for charging/discharging. Thus, EVs should make a proper decision to select proper EVCs for G2V and V2G operation. ESs provide required electricity for EVCs from the wholesale market. Furthermore, the technical challenges are mostly encountered by the power system and include voltage deviation, increasing power losses, and overload of transmission lines due to a large amount of EV charging demand [2]. Thus, an all-inclusive scheduling scheme is required to develop economic scheduling of EVs and EVCs and coordinated V2G and G2V operation of EVs. The rewards of all agents participating in charging/discharging EVs are guaranteed while considering technical constraints of the distribution network [3].

In the literature, a great deal of studies have been explored that the grid operation benefits from a proper coordinated operation of EVs [4]–[6]. The optimal planning of EV charging stations was presented considering charging EV impacts on constraints of the distribution network including voltage level, current limits in each feeder, and transformer capacity [7], [8]. The maximization of power consumption flexibility in EVCs together with a dispatch that minimizes operation costs is presented in [9] by considering a model predictive control (MPC) approach. In [10], a framework based on a hierarchical game approach was proposed to link transportation and power system together to navigate EVs to EVCs. The reliability of power system and economic profits of EV charging stations are improved effectively. The planning model of EVCs was developed to coordinate traffic-electric networks in [11]. Charging scheduling of EVs and effects of their demand on the electricity prices were developed based on aggregative game model [12]. In [13], MPC-real time formulation is proposed considering uncertainties in the electrical grid. A stochastic method was developed for charging/discharging scheduling of EVs in intelligent parking lots consisting of hydrogen storage system. The interaction of EVs with each other and the grid was considered. The costs of operation related to the distribution network and the cost of charging in intelligent parking lots are formulated as objectives of the proposed optimization problem [14]. In [15], charging/discharging management of EVs has been developed such that it has satisfied the costumers' preferences. In [16], an optimization model is presented to determine planning of EVCs which include different kinds of chargers. Furthermore, the optimal fast EVCs with integration of renewable energy resources connected to the distribution network has been presented in [18], [19].

There are numerous studies in the literature which have been

investigated that charging/discharging scheduling of EVs and EVCs do not consider a comprehensive scheme in order to guarantee benefits of all agents (e.g EVs, EVCs, ESs). Also, with increasing utilization of EVs and EVCs, no available studies focus on determining optimal day-ahead electricity prices for EV's V2G and G2V operation. The goal of this study is to develop a scheduling scheme to mainly focus on guaranteeing the rewards of all agents participating in V2G and G2V operation of EVs. Based on the proposed strategy, each EV selects a proper EVC based on the shortest driving route and the minimum cost offered by EVCs. Furthermore, EVCs select optimal ESs to purchase electricity from the wholesale market. The rewards of EVs, EVCs, and ESs are taken into account by formulating three optimization problems such that each problem belongs to each agent. The optimization problem of EVs corresponds to the minimization of the net cost of EVs. The optimization problem of EVCs and ESs is to maximize the net revenue of EVCs and ESs, respectively. At first, the EV's optimization problem is solved, and the determined decision variables are sent to the EVC's optimization problem. By solving the EVC's optimization problem, the decision variables related to the EVCs are sent to ES's optimization problem which must be solved. To implement the proposed strategy, a cloud scheduling system is considered which is an environment for collecting data from each agent, solving the three optimization problems and determining the proper EVCs and ESs for EV's V2G and G2V operations and then, sending the results to corresponding agents.

This paper is structured as follows. System description will be explained in Section 2. Section 3 formulates three optimization problems. The algorithm used for solving optimization problems is clarified in Section 4. The results of simulation are presented in Section 5. Finally, in Section 6, conclusions and recommendations are given.

II. SYSTEM DESCRIPTION

In this study, three agents including EVs, EVCs, and ESs are taken into account participating in EV's V2G and G2V operation. In this section, the relationship between all agents and the role of the cloud scheduling system are clarified.

A. Electric vehicles

It is assumed that there are EVs with known origin and destination and initial state of charge (SOC) in an area for each hour. EVs must plan charging/discharging their own batteries. EV's V2G/G2V operation is determined based on their benefit. Thus, EVs must select proper EVCs for selling/purchasing electricity during V2G and G2V operation, as shown in Fig. 1. There are multiple EVCs with different electricity prices offered for EV's V2G and G2V operation. The selection of the proper EVCs is based on the minimum driving route between EVs and EVCs and the minimum expenses during G2V operation and the maximum revenue during V2G operation.

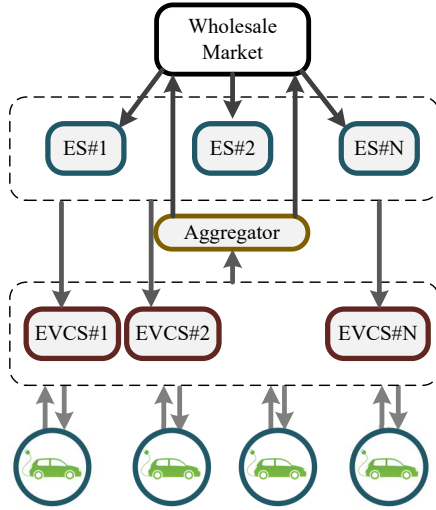


Fig. 1. Interaction between EVs, charging stations, and electricity suppliers.

B. Charging stations and aggregator

The EVCSs with known locations are installed in a city and operate in parallel with the distribution network. All EVCSs have DC rapid charging devices. EVCSs supply electricity for EVs from three sources: (i) conventional generation unit installed at location of each EVCS, (ii) photovoltaic (PV) system located at each EVCS, and (iii) energy stored in energy storage system. The generation unit that utilizes natural gas and the PV system produce electricity. If power produced is more than the electricity required for charging EVs and the energy stored in energy storage system, the excess is sold to the wholesale market through an aggregator, as depicted in Fig. 1. However, if the electricity required for charging EVs is more than the total power produced by generation unit, PV system and the energy stored in energy storage system, the electricity is purchased from ESs based on electricity prices offered by ESs.

C. Electricity suppliers

As illustrated in Fig. 1, the ESs purchase electricity from the wholesale market and arrange it to be delivered to the EVCSs when the electricity produced and energy stored in EVCSs are not sufficient for charging EVs. ESs work in a competitive electricity market, and EVCSs must choose proper ESs in order to supply electricity during charging of EVs. The selection of ESs by EVCSs is based on the minimum expenses for EVCSs.

D. Cloud scheduling system

As depicted in Fig. 2, a cloud scheduling system is an environment for collecting the following required parameters and data from each agent. EVs are connected to the cloud scheduling system whenever they want to be charged or discharged.

- Initial SOC of EV's battery for each hour;
- Origin and destination of EVs for each hour;
- Location of EVCSs;

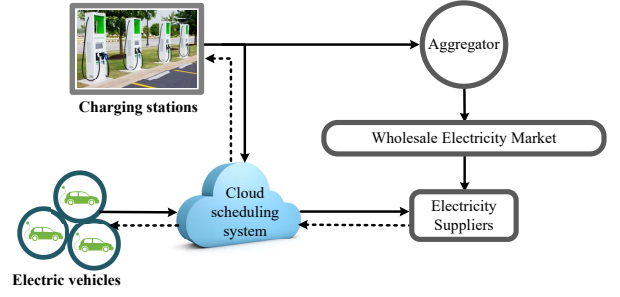


Fig. 2. Interaction of cloud scheduling system with EVs, EVCSs, and ESs.

- The number and the capacity of available chargers in each EVCS for each hour;
- Hourly electricity price of the wholesale market.

In the cloud scheduling system, the minimum driving distance between EVs and EVCSs is determined by ArcGIS software [20]. Then, the three optimization problems belonging to EVs, EVCSs, and ESs are solved and the following data will be dispatched to corresponding agents:

- Charging/discharging scheduling of EVs for a day;
- EVCSs and ESs selected by EVs and EVCSs, respectively;
- Hourly electricity prices offered by ESs for a day that is estimated by wholesale market;
- Hourly electricity price sold to the wholesale market by the aggregator;
- Power produced by the generation unit, the electricity purchased from ESs by EVCSs, and the electricity sold to the aggregator by EVCSs;
- The benefits of all agents.

III. OPTIMIZATION PROBLEMS

In this section, objective functions and corresponding constraints for EVs, EVCSs, and ESs are developed for simulation. The optimization problem of EVs corresponds to the minimization of the net cost of EVs. Charging/discharging scheduling of EVs and optimal power sold/purchased to/from EVCSs by EVs are determined by solving EV's optimization problem. For EVCSs, the optimization problem is a maximization of their net revenue. The optimal electricity produced by the generation unit in EVCSs, optimal electricity purchased from ESs by EVCSs, and optimal power sold to the aggregator by EVCSs are specified in solving EVCS's optimization problem. The optimization problem of ESs is a maximization of the net revenue of ESs. Optimal electricity prices sold to EVCSs by ESs are determined in ES's optimization problem.

A. EV's optimization problem

The objective function of EV's optimization problem is the net cost of EVs which must be minimized. The objective function is the difference between the cost of electricity purchased from EVCSs, battery degradation cost and the revenue of selling electricity to EVCSs, as given by

$$\min \left(C^{\text{EV}} = C^{\text{EV},\text{CS}} + C^{\text{DEG},\text{EV}} - R^{\text{EV},\text{CS}} \right) \quad (1)$$

Subject to:

- The SOC of EVs is limited within minimum and maximum value;
- When EVs leave the selected EVCS, the SOC must be higher than the required SOC of EV to reach to the next destination;
- There is a limitation for electricity power sold/purchased to/from EVCSs by EVs during charging/discharging period;
- At each hour, each EV must be only allocated in one of the charging or discharging mode.

The cost of electricity purchased from EVCSs and the revenue of electricity sold to EVCSs are determined by product of electricity purchased/sold by EVs and the electricity price offered by EVCSs during EV's G2V and V2G operation. Also, the degradation cost corresponds to the cycling degradation.

B. CS's optimization problem

The net revenue of EVCSs is considered as an objective function for EVCSs which has to be maximized. The net revenue can be determined by subtracting the revenue of electricity sold to the aggregator and to EVs in G2V operation from the operation cost and cost of electricity bought from ESs and EVs, as obtained by

$$\max \left(R^{CS} = R^{CS-,AG} + R^{CS-,EV} - C^{Op,CS-} - C^{CS+,ES} - C^{CS+,EV} \right) \quad (2)$$

Subject to:

- The balance between power supplied and demand in each EVCS must be fulfilled for each hour during EV's V2G and G2V operation;
- The power supplied by the PV panels is limited by the nominal power PV generated;
- The SOC of the energy storage system for each EVCS is limited by maximum and minimum value;
- It is not possible to charge and discharge energy storage system simultaneously;
- The power produced by the generation unit is maintained within a lower and upper bound;

The operation cost of each EVCS consists of the operation costs of the generation unit and chargers. The cost of electricity purchased and the revenue of electricity sold are determined by the product of electricity purchased/sold and corresponding prices.

C. ES's optimization problem

The net revenue of ESs must be maximized in this optimization problem. It is calculated as the difference between the revenue of electricity sold to EVCSs and the cost of electricity purchased from the wholesale market, as given by:

$$\max \left(R^{ES} = R^{ES-,CS} - C^{ES+,WM} \right) \quad (3)$$

Subject to:

- For each hour, the electricity purchased from wholesale market and EVCSs must be equal to sum of the total electrical load and total loss of the grid;
- The electricity bought from wholesale market must be limited based on substation transformation capacity;
- The bus voltage of distribution network must be within permissible range;
- The power flow for each bus at all time must be fulfilled;
- The electricity prices offered by ESs to EVCSs must be limited within minimum and maximum value.

IV. OPTIMIZATION ALGORITHM

Salp swarm algorithm as an evolutionary method is utilized for solving three optimization problems. This algorithm is inspired by swarming behaviour of salps when they navigate in deep oceans as a salp chain. There are two groups in the population of salps. The first group is the leader and the second group is the followers. The salp at the front of the chain is the leader and the rest of them are the followers. The position of all salps are sorted every iteration and there is a food source as the swarm's target in the search space. The position of the leader is changed based on the food source and the followers pursue the leader every iteration. The position of the leader and followers are obtained by [21]

$$x_n^L = \begin{cases} F_n + c_1 ((ub_n - lb_n) c_2 + lb_n) & c_3 \geq 0 \\ F_n - c_1 ((ub_n - lb_n) c_2 + lb_n) & c_3 < 0 \end{cases} \quad (4)$$

The position of the follower is updated by [21]:

$$x_n^f = \frac{1}{2}(x_n^f + x_n^{f-1}) \quad (5)$$

where c_1 is a variable that will exponentially decrease throughout the iterations, and c_2 and c_3 are random numbers between zero and one [21].

$$c_1 = 2e^{-\left(\frac{4 \times it}{it}\right)^2} \quad (6)$$

As shown in Fig. 3, the number of decision variables for EV's optimization problem is $(2 \times \text{Number of EVs})$ which belongs to the electricity power purchased/sold from/to EVCSs for all EVs. The number of decision variables for EVCS's optimization problem is $(3 \times 24 \times \text{Number of EVCSs})$ which

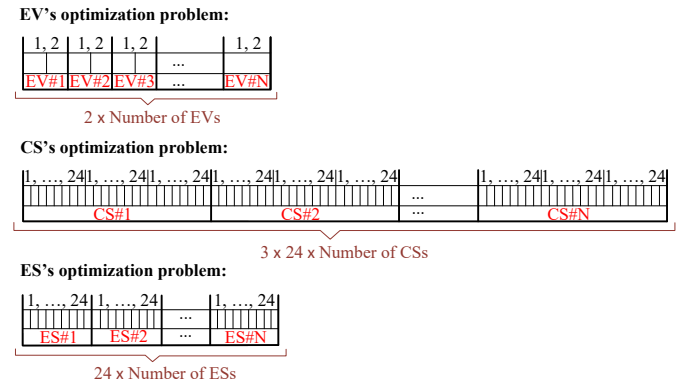


Fig. 3. Decision variables for optimization problem of EVs, EVCSs, and ESs.

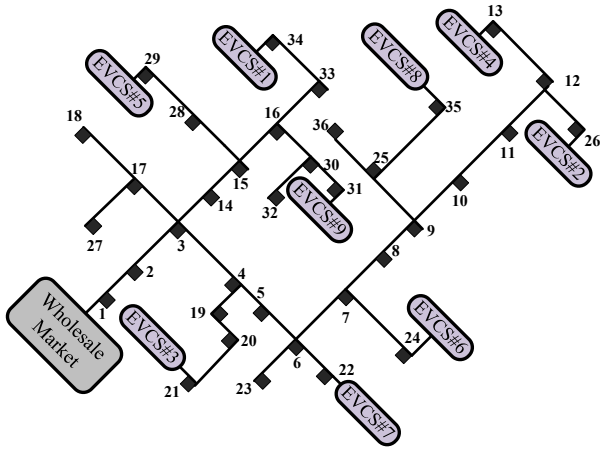


Fig. 4. IEEE 37-bus distribution test network [22].

corresponds to the power produced by generation unit in EVCSs, power purchased from selected ES by EVCSs, and power sold to the aggregator by EVCSs for each hour of a day. Also, the number of decision variables for ES's optimization problem is $(24 \times \text{Number of ESs})$ which corresponds to the hourly electricity prices offered by ESs to EVCSs. Furthermore, firstly, the decision variables of ES's and EVCS's optimization problem are initialized. Then, solving starts from EV's problem and the optimal value of decision variables of EVs is sent to the optimization problem of EVCSs. The optimization problem of EVCSs is solved and then, the optimal value of decision variables of EVCSs is delivered to ES's problem.

V. SIMULATION RESULTS

For simulation purposes, nine EVCSs are installed in a city which EVs charge/discharge their own batteries there. It is assumed that EVCSs are connected to the IEEE 37-bus distribution test network [22], as shown in Fig. 4. There are three ESs to purchase electricity from wholesale market and sell it to EVCSs. The electricity prices sold to EVs by EVCSs are considered 10-50% more than electricity prices purchased from ESs by EVCSs. It is assumed that the electricity price sold to the aggregator by EVCSs is 10% more than electricity prices EVs sold to the EVCSs during V2G operation. The proposed strategy is simulated in Python 2.7.13 environment. The simulation time is obtained for solving three optimization problems is obtained 720 seconds for all EVs.

The optimal day-ahead electricity prices offered by the greatest and least profitable EVCS (EVCS#1 and EVCS#8) during EV's G2V and V2G operation are shown in Fig. 5 and Fig. 6, respectively. The optimal hourly electricity prices offered by three ESs to EVCSs for a day are shown in Fig. 7

Based on the proposed strategy, the rewards of all agents are calculated by solving three optimization problems. The results show that by implementing the proposed strategy, the cost of EVs decreases by 18%, and the revenues of EVCSs and ESs are raised by 21% and 23%, respectively compared to the case

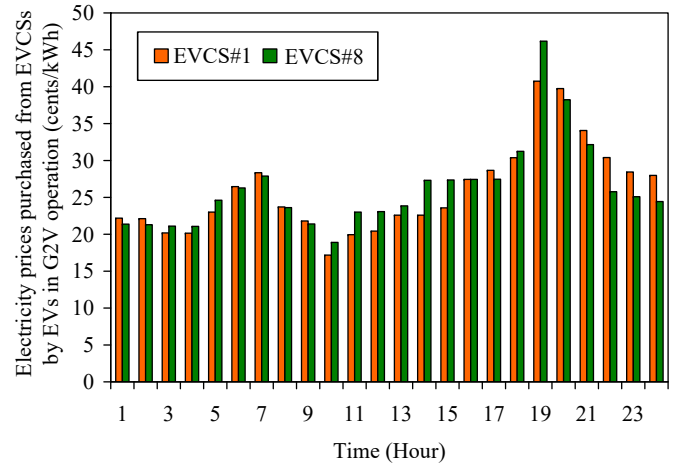


Fig. 5. Optimal hourly electricity prices offered by EVCSs to EVs during G2V operation for EVCS#1 and EVCS#8.

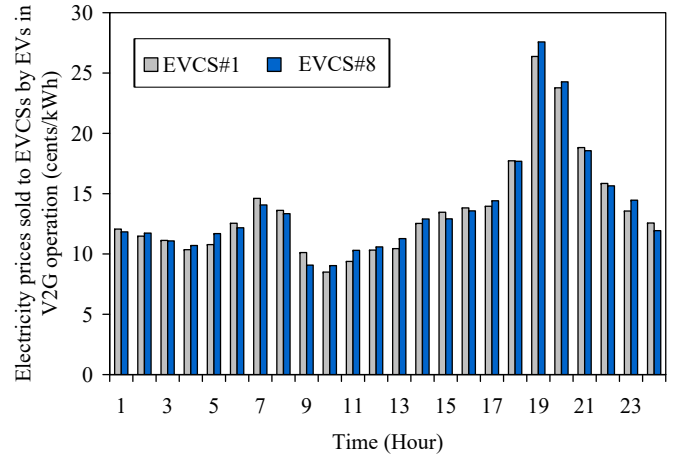


Fig. 6. Optimal hourly electricity prices offered by EVCSs to EVs during V2G operation for EVCS#1 and EVCS#8.

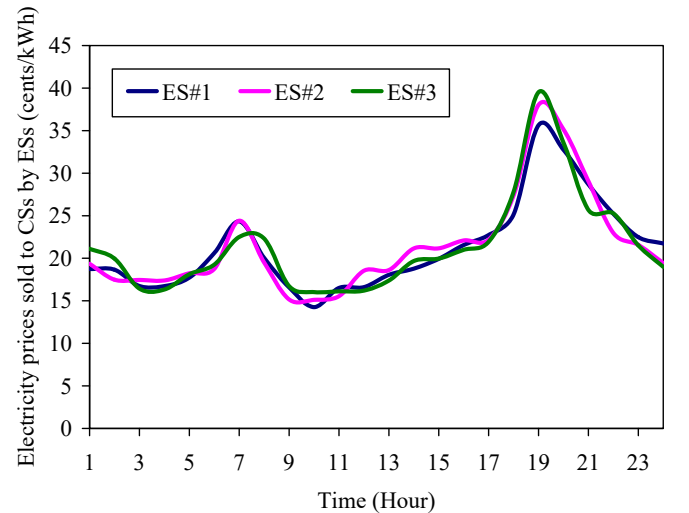


Fig. 7. Optimal hourly electricity prices offered by three ESs to EVCSs.

in which EVs do not use the proposed strategy in EV's V2G and G2V operation.

VI. CONCLUSION

In this study, an all-inclusive scheduling scheme is developed to propose economic scheduling of EVs and EVCSS and coordinated V2G and G2V operation of EVs. The rewards of all agents participating in charging/discharging EVs are guaranteed while considering technical constraints of the distribution network. Based on the proposed scheduling strategy, EVs independently plan their charging/discharging depending on the minimum driving route and cost/benefit offered by EVCSS and find proper EVCSS. Also, EVCSS select optimal ESs to purchase energy. The rewards of all agents in EV charging/discharging are analysed by solving three optimization problems belonging to all agents. To implement the proposed strategy, a cloud scheduling system is operated to collect required information from all agents, solve the optimization problems, and ultimately send the results to relevant agents. Optimal day-ahead electricity prices offered by EVCSS for V2G and G2V operation and electricity prices offered by ESs to EVCSS are determined in this study. For future work, the cooperative and non-cooperative game theory in order to model the interaction between different agents is recommended.

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